Modeling the Acoustic Channel for Simulation Studies

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LONG-TERM GOALS

Underwater acoustic communications, especially from a single point-to-point link perspective, have been studied extensively in the past few decades. Underwater networking issues have begun to attract the interest of researchers as well, and represent a fertile research area which can be expected to grow in the future. Bringing the study of acoustic communications systems to the networking level has the potential to open up new directions and to provide a means to make them much more powerful and useful. Many military and naval applications can be expected to greatly benefit from this paradigm shift.

The main goal of the proposed work is to deepen our understanding of the behavior of the underwater acoustic channel and develop channel modeling techniques to enable more detailed studies at the networking level. To this aim, we started from existing data sets for point-to-point communications, in order to try and extract fundamental behaviors and model them in a way suitable for the simulation of more complex systems. This includes the integration of existing (as well as new) acoustic propagation modeling techniques into network simulators, the search for statistical models based on measured data, as well as the development of trace-based simulation techniques, and their validation and assessment in representative application scenarios.

OBJECTIVES

The project started on 04/01/10, and the reporting period covers from 09/01/10 to 08/31/11. The main objective for this period was to gain deep insight on the propagation phenomena that most affect underwater acoustic systems, based on the experimental data made available to us. Key behaviors have been sought and quantified, including sparsity, stationarity, and predictability. Insights on how these channel properties can be used for system design have been developed. Some application examples where this understanding can be productively used have been considered, including adaptive modulation, image coding, and routing.

APPROACH

The objective of the proposed research work is to develop simulation models able to correctly capture the behavior of acoustic propagation in underwater communication networks, while containing the

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proper level of detail that makes them realistic while still sufficiently lightweight for use in networking simulations.

The technical approach we proposed to adopt in the overall effort includes the following points: (i) deep interdisciplinary understanding of acoustic propagation environments and networking capabilities/requirements; (ii) identification and evaluation of the main PHY metrics that need to be used in networking studies; (iii) development of comprehensive simulation models that accurately reproduce the propagation characteristics of underwater channels, while also being suitable for use in networking studies; (iv) validation of the proposed models in the performance analysis of advanced communications and networking functionalities through detailed analysis, simulation, and experimentation.

In the reporting period (month six through month seventeen), we focused on all points above. In particular, we (i) deepened our understanding of acoustic propagation and its implications on system design; (ii) studied relevant PHY communications metrics according to the systems considered (including SNR, BER, channel impulse response, stationarity intervals, correlation coefficients, channel estimation errors) as well as higher-layer metrics (including throughput, delay, outage probability, packet delivery ratio, PSNR); (iii) improved our simulation framework and developed new statistical models for sparse channels; (iv) applied the gained understanding to relevant application scenarios.

We highlight that the overall objectives are very ambitious and can be addressed from different (but complementary) points of view. The body of work we developed during these twelve months can accordingly be categorized following several complementary approaches. An *inductive* approach was used in some of our studies, where we started from the data sets to extract information about the channel behavior, trying to highlight patterns (e.g., periodicity) and to verify some broad assumptions (e.g., stationarity). From the data we were able to infer some useful information about the channel behavior on different time scales, which then allowed us to make some modeling assumptions based on experimental evidence. A complementary *deductive* approach was instead used when a model was assumed and was then verified/validated against the experimental data. For example, this is the case for the hybrid sparse/diffuse model we developed or for the assessment of different prediction strategies. Finally, we also adopted a *simulation based* approach, where experimental evidence is replaced by simulated data, which is easier, faster, and cheaper to obtain and makes it possible to study scenarios that are too difficult to experiment with.

The current project team includes Prof. Michele Zorzi (PI), Prof. Gianfranco Pierobon (co-PI), Drs. Paolo Casari and Alfred Asterjadhi (post-doctoral researchers) and Ms. Beatrice Tomasi and Mr. Nicolo' Michelusi (Ph.D. students).

WORK COMPLETED AND RESULTS

The focus of the work in these twelve months of the project has been the following: (i) to acquire relevant data sets and to process them; (ii) to investigate interesting and useful channel behaviors/properties starting from the experimental data, both analytically and by simulation; (iii) to further the development of our simulation framework; and (iv) to provide some application examples of how the understanding we gathered can be fruitfully used.

As to point (i), *acquisition and analysis of data sets*, we have been able to gain access to the following data sets: SPACE08, SUBNET09 and KAM11. As the SUBNET09 dataset was described in the previous report, we focus here on the other two.

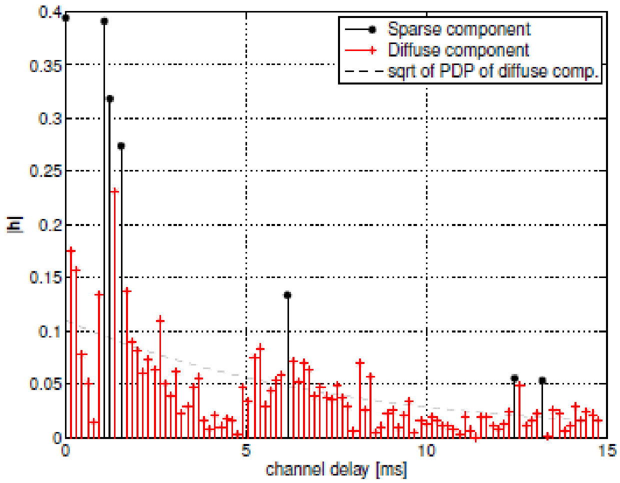
The SPACE08 experiment was conducted during the month of October 2008 at the Martha's Vineyard Coastal Observatory (MVCO) operated by the Woods Hole Oceanographic Institution. The scenario consists of one transmitter and six fixed receiving stations, each of which is equipped with several hydrophones. The data set is particularly interesting because the environmental conditions such as the surface wave characteristics and wind speed and direction varied significantly over the duration of the experiment. While the collected data sets are from only one deployment, the impact of surface variability on acoustic channel stationarity is more generally interpretable in other scenarios with similar geometries. A more detailed description of the experimental setting as well as of the experiments performed can be found in [EW11].

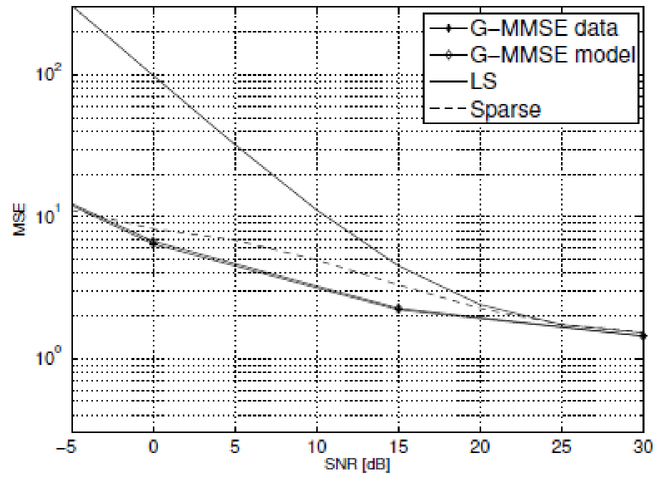
The KAM11 data set has been collected in 2011 during Julian dates from 171 to 191, off the coast of Kauai Island. The scenario was stationary: the source and the receiver were 3 km apart and positioned at 45 m below the ocean surface. The receiver used signals received at a 24 element vertical and linear hydrophone array with 5 cm spacing between hydrophones. The equalizer used to generate the results shown here utilized signals from 4 of the hydrophones spaced by 15 cm. The central frequency and bandwidth of the omni-directional source were 13 kHz and 8 kHz, respectively. A more detailed description of the experimental setting as well as of the experiments performed can be found in [WUWNET11_KAM11].

The experiments consisted of transmissions of a variety of acoustic waveform, and data that was collected includes SNR values, channel impulse responses, error rates, etc.

As to point (ii), *understanding of channel behaviors*, we have focused on three main characteristics of the statistical behavior of the acoustic channel, namely, sparsity, stationarity, and predictability/periodicity.

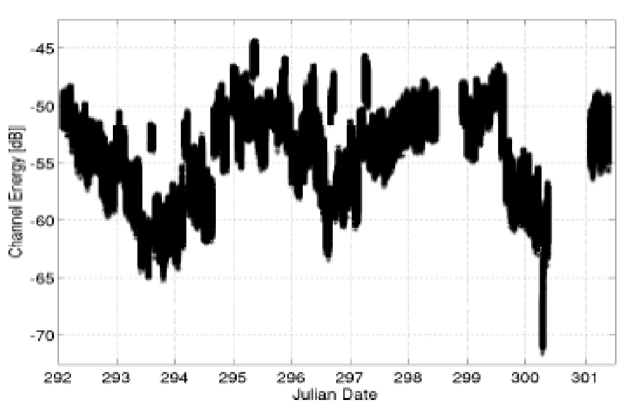
We proposed a model to represent the *sparsity* of the underwater channel. Contrary to models found in the literature that focus on purely sparse or purely diffuse representations, we proposed a mixed sparse/diffuse model. Such a model has been theoretically analyzed and characterized, and has been used to derive some channel estimators. The figure below on the left depicts an example of the energy content of the impulse response of an acoustic channel, showing that both sparse and diffuse components are significant. The figure on the right compares the performance of different channel estimators, showing that the ones based on the proposed model perform much better than LS and also outperform estimators based on the assumption that the channel is purely sparse.



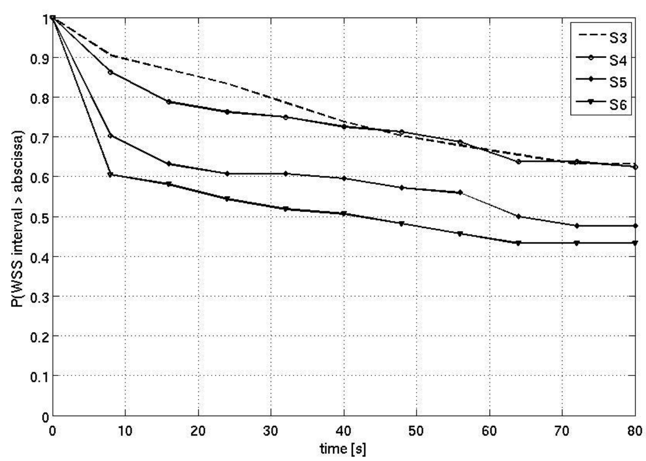


Various additional results, as well as a thorough analytical development, can be found in [OCEANS11_HSD, ALLERTON11].

We studied the random process that represents the channel behavior (e.g., in terms of the SNR time evolution) and have studied its *wide-sense stationarity*. This study is useful in several instances, for example in order to understand when some well-established statistical signal processing techniques can be used. We have considered both non-coherent and coherent transmission systems. Statistical stationarity tests have been run on the data, with different sizes of the stationarity test interval, in order to assess on which time scales the channel could be considered as stationary. Time scales of interest include fractions of second (for PHY) as well as tens of seconds (for MAC and networking). An example of the time series of the channel energy measured at the receiver and an example of the complementary cumulative distribution function of the stationarity interval are given below (left and right, respectively).

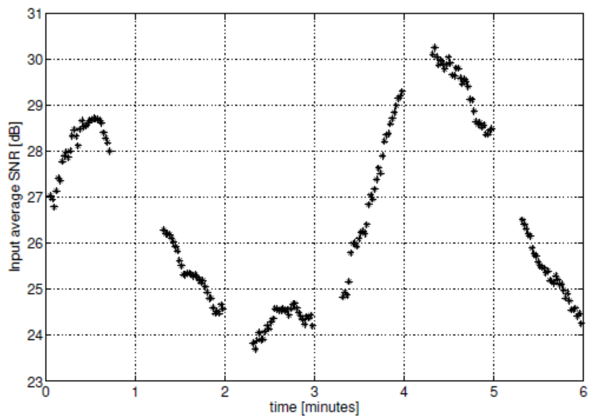


(a) Channel energy time series at S5 from Julian Date 295 to 301.

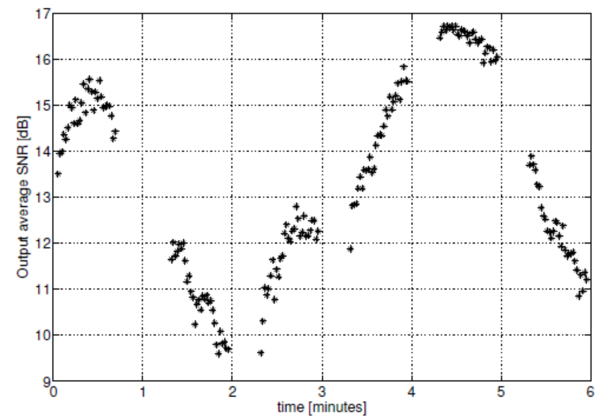


The results presented in [UAM11_WSS, EW11] show that it is often possible to consider the channel as stationary on the time scales of interest, although this depends on whether the communications system is coherent or non-coherent.

We have studied the possibility to predict channel behaviors in time, in order to reduce the impact of a feedback loop. In particular, analysis of the data sets has revealed both some periodic behaviors that could be fruitfully used to accurately predict future channel conditions (e.g., to drive scheduling strategies), and some significant predictability of the channel conditions based on past evolution and more or less sophisticated prediction techniques. An example of periodic behavior observed in the data is given below.

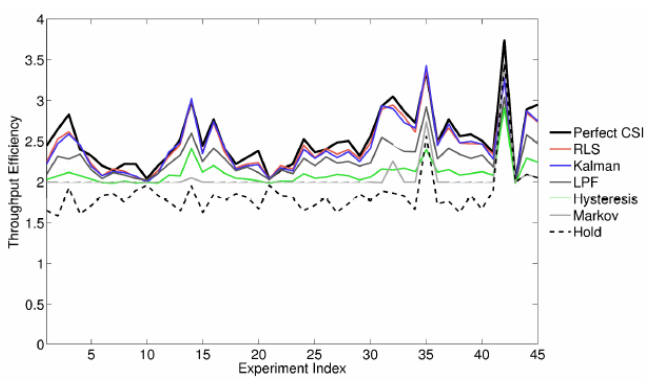


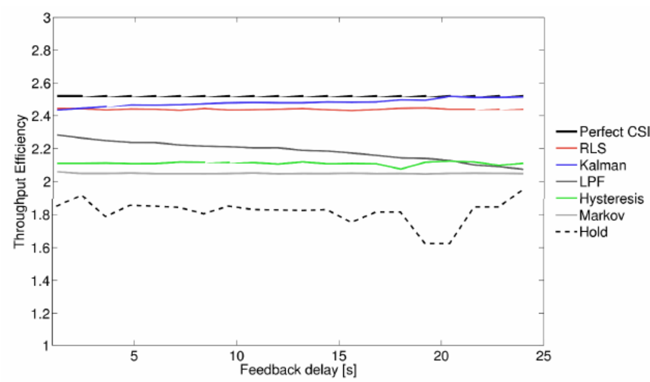
(a) Average input SNR at Julian date 187, at 4 am.



(b) Average output SNR at Julian date 187, at 4 am.

We have compared several possible prediction techniques, and have quantified their performance when they are used for adaptive modulation, where the modulation scheme is dynamically changed according to the estimated channel conditions. An example of the results we obtained is given below, showing that with appropriate prediction techniques it is possible to achieve performance close to that obtained when perfect channel information is available.





More details and additional results on these topics have been reported in [UAM11_PRED, WUWNET11_KAM11].

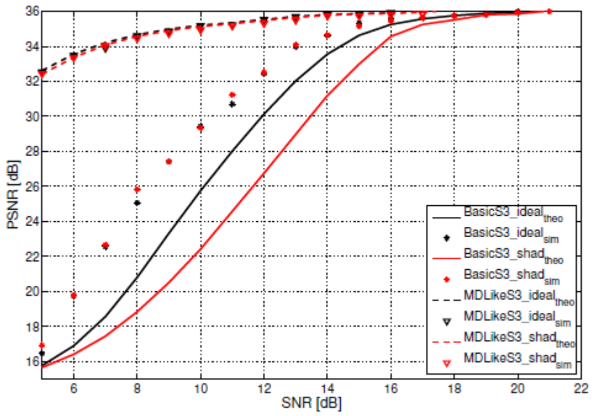
We highlight that our efforts on these investigations of the channel behaviors were mainly targeted to *temporal* quantities and relationships (stationarity, periodicity, time-correlation, predictability in time, sparsity). A very interesting complementary study which is part of our planned future work is to addess the *spatial* dimension of this problem, trying to understand what is the variability in space and how it can be characterized.

As to point (iii), *development of simulation platform*, we have further developed our WOSS simulator, including new PHY features that make its PHY processing more accurate. We have also started working on interfacing the ns-2 network simulator directly with the WHOI micromodem, which would allow emulation of communication schemes and protocols directly in the water while maintaining complete reconfigurability of the protocol levels. Finally, we are currently working on porting WOSS into ns-3, which is the next generation of the network simulator that is gradually being adopted in the research community worldwide.

As to point (iv), *application examples*, we have studied a few application scenarios in which the understanding of the channel behavior described above can be put to good use. These include adaptive modulation, image coding, and routing.

Example results on the transmission efficiency of adaptive modulation schemes with channel prediction have been given above and are extensively reported in [UAM11_PRED, WUWNET11_KAM11].

A comparison of image coding techniques when used in an underwater acoustic communications system has been performed. In particular, progressive source coding was used to encode the image, and unequal error protection was adopted. How to allocate FEC redundancy to the various information bits was studied, and in particular two algorithms (Basic and Multiple-Description based) were compared. The effect of channel knowledge was also studied, by comparing a system where the transmitter (that does FEC allocation) is assumed to know the instantaneous channel conditions (ideal), with one where only average channel quality is known (shad). PSNR results are shown in the figure below (left), where it can be seen that the MD-based scheme greatly outperforms the basic scheme, and is significantly more robust to imperfect channel knowledge. The figure to the right instead shows visually the quality of the reconstructed image, and it can be seen once again that the MD-based scheme (bottom row) outperforms the Basic scheme (top row).



(a) Basic allocation scheme, SNR=6 dB, PSNR=19.7 dB.

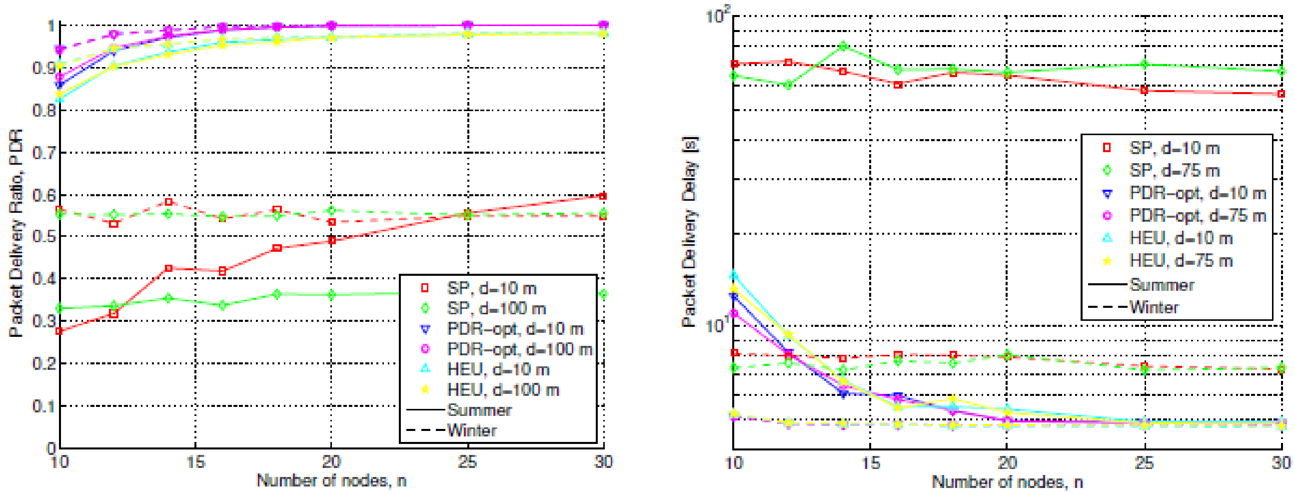
(b) Basic allocation scheme, SNR=12 dB, PSNR=32.3 dB.

(c) MD-Like allocation scheme, SNR=6 dB, PSNR=33.4 dB.

(d) MD-Like allocation scheme, SNR=12 dB, PSNR=35.6 dB.

More details on this study can be found in [WUWNET11_SPIHT].

Finally, we studied how the insights on channel behavior, and in particular the seasonal variability of the sound propagation characteristics, can help design effective routing schemes. In particular, we considered shallow-water acoustic networks, and proposed a routing policy that exploits qualitative information about the behavior of the channel, given some key parameters such as the position and depth of the source, the location of the receiver and the sea bottom profile. Our policy is based on a set of several synthetic channel realizations obtained using the Bellhop ray tracing software, where the channel variability is obtained via random perturbations of the sound speed profile and of the sea surface shape. The channel realizations are translated into Signal-to-Noise Ratio (SNR) statistics: the relay sought must comply with the constraint that the SNR exceeds a threshold with a given probability. We show that these SNR statistics allow the routing policies to identify geographic areas where a high SNR is more likely to occur. Our policy is compared to shortest-path routing (obtained via a centralized algorithm and oblivious of channel statistics), and to an optimal, genie-aided policy that always picks the best relay which complies to the SNR constraint. An example of the obtained results is given below, where it is shown that shortest-path (SP) routing is greatly outperformed by the proposed scheme (HEU), which is always very close to the optimal (PDR) policy.



More details on the schemes and additional results can be found in [OCEANS11_ROUTING].

IMPACT/APPLICATIONS

Many of the behaviors revealed by our analysis, as well as some of the schemes proposed, are novel, and are expected to shed some light on how propagation affects the performance of underwater communications systems. The applications we considered provide a representative set of cases in which our insights were found to be useful. We expect that these results will provide an interesting starting point to other researchers and will stimulate creative work.

RELATED PROJECTS

During the reporting period, the PI has been involved in an NSF project at UC San Diego (CNS-1035828 CPS: Medium: Collaborative Research: Networked Sensor Swarm of Underwater Drifters), an interdisciplinary effort including localization, networking, and ocean science. While there is essentially no overlap with the current project, it is possible that as part of that effort we will be able to perform some ad hoc channel measurements that will provide some additional data for our analysis. The PI has also had some related efforts funded by the European Commission and by an Italian foundation. The focus of such efforts is more on protocol design than on channel modeling and therefore those projects are complementary and non-overlapping with respect to the present one.

PUBLICATIONS

During the reporting period, nine papers have been published and/or accepted, all carrying the acknowledgement to ONR funding. The following conference papers include technical achievements of the project and have been referenced in this report (journal versions are currently in preparation):

[EW11] Beatrice Tomasi, James Preisig, Michele Zorzi, "A Study on the Wide-Sense Stationarity of the Underwater Acoustic Channel for Non-coherent Communication Systems," in Proc. of European Wireless, Vienna, Austria, Apr. 2011.

[UAM11_WSS] Beatrice Tomasi, James Preisig, Michele Zorzi, "A Study on the Wide-Sense Stationarity of the Underwater Channel for Coherent Systems," in Proc. of UAM, Kos, Greece, Jun. 2011.

[UAM11_PRED] Paolo Casari, Beatrice Tomasi, Konstantinos Pelekanakis, Mandar Chitre, Michele Zorzi, "Performance Evaluation of SNR Prediction Schemes in Acoustic Communication Systems using Variable-Rate Modulation," in Proc. of UAM, Kos, Greece, Jun. 2011.

[ALLERTON11] Nicolò Michelusi, Urbashi Mitra, Andreas Molisch, Michele Zorzi, "Hybrid Sparse/Diffuse Channels: a New Model and Estimators for Wideband Channels," in Proc. of Allerton Conference, Monticello, IL, Sep. 2011.

[OCEANS11_HSD] Nicolò Michelusi, Beatrice Tomasi, Urbashi Mitra, James Preisig, Michele Zorzi, "An Evaluation of the Hybrid Sparse-Diffuse Algorithm for Underwater Acoustic Channel Estimation," in Proc. of IEEE OCEANS, Hawaii, Sep. 2011.

[OCEANS11_ROUTING] Paolo Casari, Alfred Asterjadhi, Michele Zorzi, "On Channel-Aware Routing Policies in Shallow-Water Acoustic Networks," in Proc. of IEEE OCEANS, Hawaii, Sep. 2011.

[WUWNET11_KAM11] Beatrice Tomasi, James Preisig, Michele Zorzi, "On the Predictability of Underwater Acoustic Communications Performance: the KAM11 Data Set as a Case Study," Proc. ACM WUWNet, Seattle, WA, Dec. 2011.

[WUWNET11_SPIHT] Beatrice Tomasi, Laura Toni, Paolo Casari, Michele Zorzi, "A Study on the SPIHT Image Coding Technique for Underwater Acoustic Communications," Proc. of ACM WUWNet, Seattle, WA, Dec. 2011.

In addition, we also published the following high-profile survey paper that, while not containing original results, deals with some of topics at the core of this effort, such as simulation and channel modeling:

John Heidemann, Milica Stojanovic, Michele Zorzi, "Underwater Sensor Networks: Applications, Advances, and Challenges," to be published in the Philosophical Transactions of the Royal Society A, 2011.

Copies of these papers can be downloaded from www.dei.unipd.it/~zorzi/ONR2011

HONORS/AWARDS/PRIZES

Michele Zorzi:

- IEEE Fellow, 2007
- Member-at-Large of the IEEE Communications Society Board of Governors, 2009-2011
- Editor-in-Chief of the IEEE Transactions on Communications, 2008-present
- Editor-in-Chief of the IEEE Wireless Communications magazine, 2003-2005

- Editor for Europe of the Wiley Journal on Wireless Communications and Mobile Computing
- Keynote Speaker, European Wireless conference, Lucca, Italy, Apr. 2010. (Address was on protocol design issues and channel modelling in underwater acoustic networks.)
- Keynote Speaker, Wireless Days conference, Venice, Italy, Oct. 2010. (Address was on protocol design issues and channel modelling in underwater acoustic networks.)
- Best Paper Award, IEEE MobiWac Workshop, June 2005
- Best Paper Award, IEEE CAMAD, June 2006
- Best Paper Award, IEEE GLOBECOM (Wireless Networks Symposium), November 2007
- Best Tutorial Paper Award, IEEE Communications Society, 2007
- Best Paper Award, European Wireless Conference, May 2009
- Guest Editor of several special issues, and in particular: "Underwater Acoustic Communications and Networks," *IEEE Journal on Selected Areas in Communications*, December 2008)
- Member of the organizing and technical program committees of many conferences, and in particular: Technical Program co-Chair, ACM WUWNet'07